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Evaluation of Electrical Resistivity Characteristics of Metalized 4H-SiC for Application to Electric Guns

by Gary L. Katulka

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Abstract

The experiments described demonstrate the electrical behavior of SiC and metal ohmic-contact layers as a function of thermal stress. It has been determined from these experiments that both titanium (Ti) and tantalum (Ta) metalization structures will provide a stable electrical ohmic-contact with n-type SiC after exposure to elevated temperatures for short bursts of time that are considered relevant for pulsed-powered electric weapon technologies. The Ti-SiC structure investigated exhibited a stable current-voltage (I-V) characteristic to as much as 800° C for a 10-min burst, while Ta metalizations provided a stable I-V characteristic on SiC even after a temperature burst of 1,000° C for as long as a 3-min interval. For samples of n-type, 4H SiC, metalized with (Ti), the standard deviation in resistance (resistivity) of the measured samples is less than 0.17 ohms for a sample having an average resistance of 4.45 ohms. For the Ta contact on SiC, the standard deviation in resistance is 0.05 ohms for a sample having an average resistance of 4.25 ohms. The experiments showed that for both Ti and Ta metalized SiC samples, the change in resistivity of annealed samples is between 3.8% and 1.2% compared to the average values of sample resistance based upon the I-V measurement technique used. These results indicate the ability of Ti-SiC and Ta-SiC structures to perform in a stable manner without significant electrical degradation to the metal contact, SiC substrate, or the metal-semiconductor interface as a function of high-temperature burst conditions.

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1. Introduction

Improved weapon performance can be quantified in terms of increased muzzle kinetic energy (KE), greater armor penetration, shorter projectile time of flight, or improved target accuracy. Advanced high-power electric weapon concepts such as electrothermal-chemical (ETC) or electromagnetic (EM) gun systems, which are illustrated in the representative diagrams of Figure 1, have the demonstrated ability to improve the ballistic performance by as much as 30% over conventional guns with respect to projectile muzzle KE in ETC guns, or up to as much as 7 km/s muzzle velocity with EM railguns [1, 2].

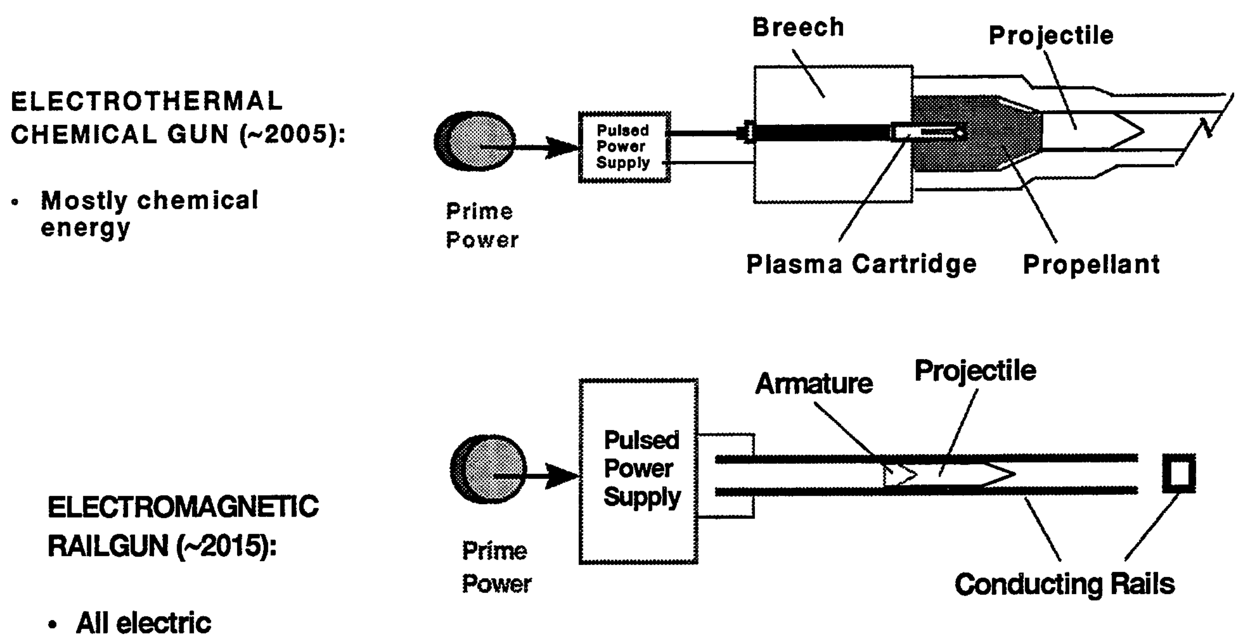

Figure 1. ETC and EM Railgun Concepts.

Other benefits of ETC gun technology include the ability to improve the ignition reproducibility by as much as a factor of 25–75 over large-caliber conventional chemical guns, which may have direct benefits toward lethality improvement due to increased target accuracy [3]. However, in order to fully provide the performance benefits offered by electric gun technologies, the integration of optimized high-power and high-temperature materials must be provided first. High-power materials will allow for improved reliability of pulsed-powered electric gun components or extend peak power capability, thereby minimizing the mass and volume of electric gun pulsed-power supplies. In addition, with the integration of optimized power electronics, the mobility of future combat systems can also be improved compared to current conventional combat vehicles due to reductions in system mass and volume as well as due to the improvements possible with electric vehicle propulsion and suspension technology that are presently under investigation.

From an electronic materials viewpoint, the compound single-crystalline semiconductor silicon carbide (SiC) is considered an excellent candidate for high-energy, pulsed-power electronics applications involving electric weapon technology. This is due to the fundamental material and electronic properties of SiC, which include its wide bandgap (2.3–3.2 eV), its high thermal conductivity (4.9 W/cm-K), its high melting point (3,000° C), and its electronic transport properties that may provide advanced electronic device designs having high blocking voltage and high-power transmission capability [4, 5]. The main advantages of SiC pulsed-power systems compared to conventional Si systems are improved lifetime and reliability at high temperatures as well as reduced material mass and volume, which are allowable due to the greatly improved voltage, power, and temperature handling that are possible with devices fabricated in SiC. In order to realize the significant potential gains with SiC materials and devices, however, large-area prototype samples operating in the anticipated system environments must first be characterized. While single-crystalline SiC can theoretically perform well under extreme conditions, the material must first interact reliably with a metal contact in a stable manner.

To determine the feasibility of a SiC-metal contact operating at elevated temperatures for periods of time relevant to electric weapon concepts, experiments have been carried out with single-crystalline, 4H (hexagonal crystal), n-type SiC. The SiC samples under study were obtained from Cree Research, Inc., and metal contacts were deposited by sputtering with metal layers, which followed by annealing at high temperatures for varying amounts of time. Resultant samples were characterized with a current-voltage (I-V) measurement technique to first test for an ohmic (nonrectifying) contact and also to characterize the thermal stability of the electrical properties at elevated temperature over varying lengths of time. The duration of high-temperature annealing was as long as 5 min, and all samples were annealed in an argon environment to avoid unwanted impurity contamination from oxygen or nitrogen into the metal-semiconductor layers.

Ultimately, more detailed analysis such as x-ray diffraction (XRD) and transmission electron microscopy (TEM) can be applied to the analysis to determine long-term effects of high temperatures on the characteristics of tested samples. The preliminary experimental results show that the titanium (Ti) and tantalum (Ta) layers on n-type SiC substrates provide stable ohmic contacts even after exposure to temperatures as high as 800 and 1,000° C for short periods of time. The Ta-SiC contacts had a smaller deviation in resistance over a larger temperature range than the Ti-SiC contacts. It is concluded that based upon preliminary I-V measurement results of the metal-SiC samples at the temperatures and periods of time investigated that the prototype materials are favorable for pulsed-power electric gun device applications.

2. Benefits of SiC in Electric Gun Missions

Significant advantages can be realized from high-temperature pulsed-power materials such as those necessary for electric combat systems. The main advantage of SiC for electric gun applications is in the ability to operate under high-current density and high-temperature conditions. The higher operating temperature in SiC is allowable due to the fact that the temperature at which thermally generated carriers in the bulk material exceed the dopant concentration is above 900° C, compared to 200° C for equivalently doped Si [6]. The overall system benefit with novel SiC power electrical systems is the reduction in mass and volume of pulsed-power components, which effectively increases the specific energy density of an electric gun pulsed-power system.

To illustrate the benefit of high-temperature capability, the results from calculations shown in Figure 2 provide an approximation of solid-state material mass required as a function of assumed

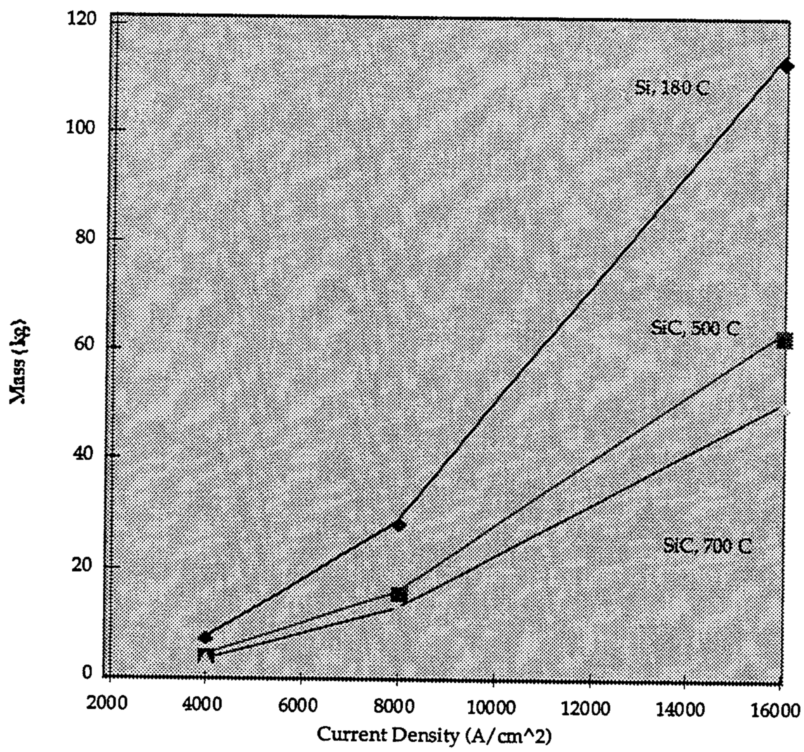

Figure 2. Calculated Solid-State Material Mass as Function of Current Density for a 3-ms Power Pulse and a Semiconductor Dopant Concentration of 1 × 1014 cm–3.

operating current density. The calculations are based upon the simplified expression for total energy, Q, deposited to a given mass, m, having a known specific heat, C, for an allowed temperature rise, ΔT, as indicated in

$$\Delta Q = mC\Delta T = \int P dt = \int I^2 R dt. \tag{1}$$

The resistance of the material for (1) is calculated from the simple resistivity expression for a semiconductor, which is

$$\rho = \frac{1}{q\mu N_D}, \tag{2}$$

where q is the electronic charge, μ is the carrier mobility, and N_D is the dopant concentration. At a given current, as indicated in Figure 2, significant reductions in mass can be realized through the use of SiC due to its improved tolerance of higher temperature. The higher maximum intrinsic temperature (900° C for SiC vs. 200° C for Si) allows for increased maximum current density or reduced solid-state mass for a given current density. As indicated in Figure 2, SiC operating at 500° C and 700° C results in mass reductions of approximately 45% and 60%, respectively, compared to the conventional Si pulsed-power counterpart, which is limited to a 180° C operational temperature.

Other electric gun applications of high-temperature materials include railgun contact materials or ETC plasma generator device components, which can also potentially provide improved weapon performance due to reduced rail erosion in EM guns or improved surface ablation properties for plasma generator components in ETC guns. With EM weapons systems, it is typical to achieve high current densities in rails and armatures, and in ETC guns high-temperature plasma sources are generated that can produce detrimental effects to electrical conducting metallic components. In recent tests conducted on EM rail material, for example, it has been demonstrated experimentally that a simulant aluminum (Al) armature on a Ti substrate produced the best performance in terms of minimizing rail material deposition [7]. In addition, ETC gun plasma sources are known to operate in the 10,000–20,000 K temperature region, which can potentially lead to metal surface erosion and alterations to the low molecular weight plasma that is sought for ETC ignition and combustion control [8, 9]. It has been reported that a significant percentage (14–23%) of the total energy contained in the typical ETC plasma source is consumed by ablation and dissociation of polyethylene and copper components of ETC plasma generators [1]. In EM and ETC guns, the use of novel high-temperature materials such as metal-SiC structures can potentially lead to significant improvements to the lifetime or overall performance of future combat systems of interest to the Army.

3. Experimental Procedure and Results

The experimental approach was to develop a feasibility analysis of various candidate high-temperature materials to determine the electrical performance as a function of elevated temperatures under burst conditions. The candidate materials were metal-SiC systems that are expected to perform reliably at elevated temperatures. A study of the literature on SiC systems for non-pulsed-power applications indicated that Ni, Ti, Ta, and W metals on SiC perform well with regard to specific contact resistance [10]. Ti and Ta are chosen here as metals for SiC due to their known high melting temperature (1,660° C and 2,990° C, respectively), demonstrated erosion properties (with Ti), and a history of quality ohmic contacts achieved with SiC substrates for other non-pulsed-powered applications [11, 12, 13].

4. Ti-SiC I-V Results

The results of the current-voltage (I-V) characteristics, obtained as illustrated by the simplified schematic diagram in Figure 3, of the Ti-SiC samples examined are given in Figures 4–6. The I-V characteristics are obtained by the measurement of the current flowing through the metalized sample as a function of the junction voltage applied across the sample. As shown in Figure 3, the current is monitored by an ammeter (Fluke 87) as a function of applied voltage, which is provided from a calibrated DC voltage generator (Datel 8500). Results from I-V measurements of a Ti-SiC sample are shown in Figure 4.

The two I-V measurement curves shown are for a Ti-SiC sample "as-deposited" and after a 600° C anneal in forming gas (85% N_2, 15% H_2) for a burst of 5 min. As indicated by the measurements, the annealed sample displays a reduced slope, which reflects an overall increase in resistivity by about a factor of 2. The reason for the unexpected increased resistivity displayed by the annealed sample is not clear, but may be due to the relatively low annealing temperature used. A temperature of 600° C may not be high enough to form a desirable silicide phase at the metal semiconductor interface, which is generally known to reduce contact resistivity and

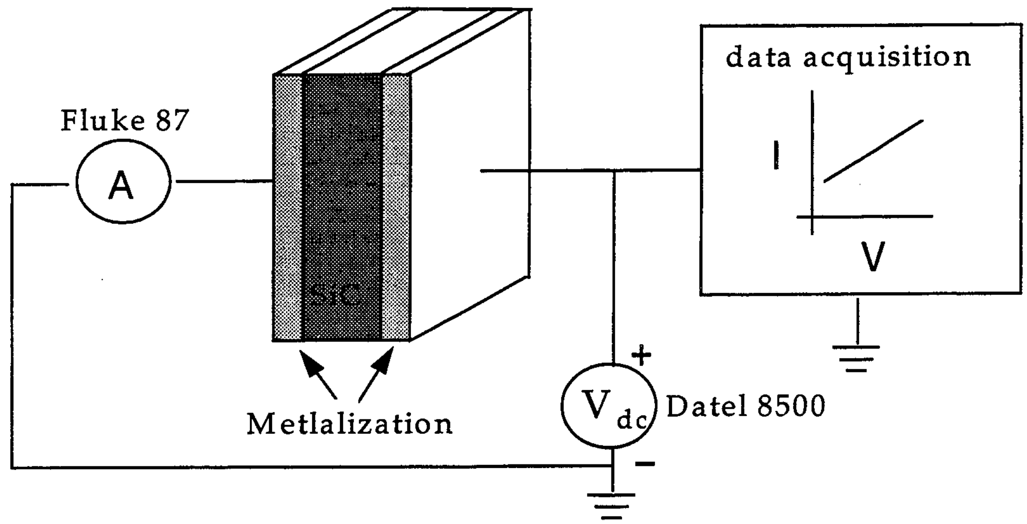

Figure 3. Electrical (I-V) Characterization Arrangement for Metalized SiC Sample Materials.

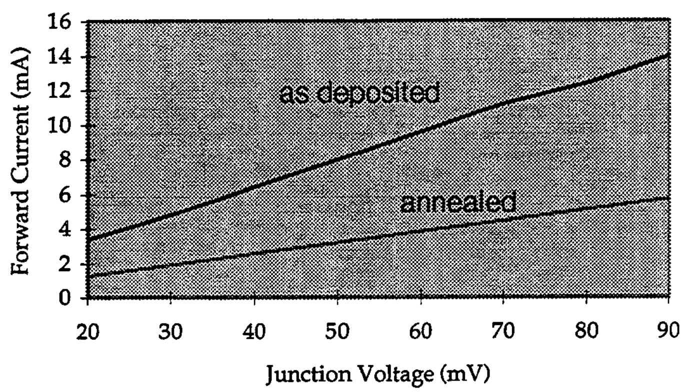

Figure 4. Ti-SiC Sample As-Deposited and Annealed at 600° C for 5 min.

provide a stable ohmic contact [14]. The second reason may be the nitrogen content of the forming gas that was used during the annealing to reduce the effects of oxygen. It is considered unlikely but possible that a nitride phase was formed during the anneal that contributed to the degradation in contact quality as indicated by the increase in resistivity. Steps taken to alleviate this problem included increasing the initial anneal temperature to above 1,100° C, where Ti-SiC phases are known to form [15], and using argon as the ambient gas during all high-temperature

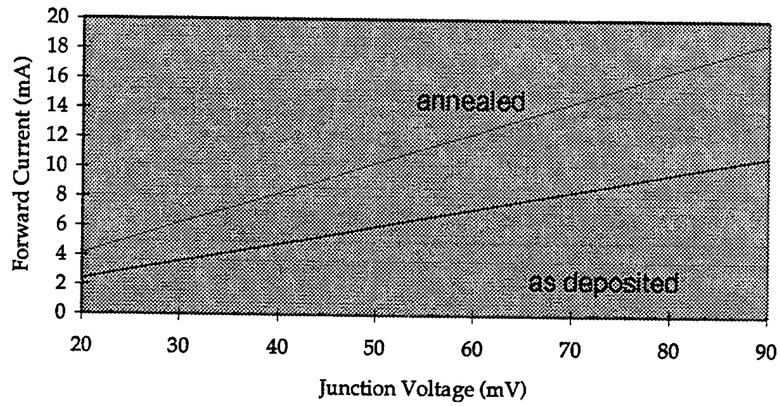

Figure 5. Ti-SiC Sample as-Deposited and Annealed at 1,120° C for 2 min.

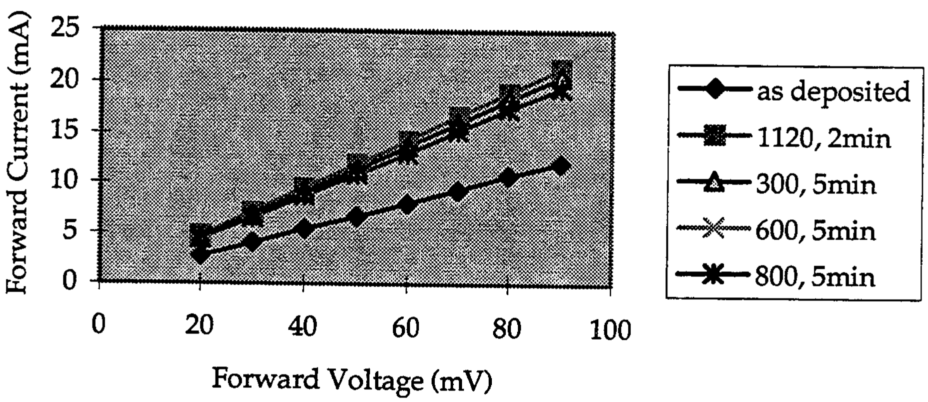

Figure 6. Ti-SiC Sample I-V Characteristics for As-Deposited and Annealed Samples at 300, 600, 800, and 1,120° C.

steps to remove the possibility of nitride formation on the sample surfaces. The I-V results of a second Ti-SiC sample annealed at 1,120° C for 2 min in argon are shown in Figure 5, together with the "as-deposited" curve. Figure 5 shows that the Ti-SiC contact resistance decreased after annealing in argon, in contrast to the increasing resistance observed in Figure 4. It is believed that this important change is due to the substitution of argon-forming gas, which prevented the formation of a nitride. Further high-temperature annealing was performed on the Ti-SiC sample having the I-V characteristics of Figure 5. Annealing was performed at 300, 600, and 800° C for a 5-min duration at each level, and an I-V measurement was performed at the completion of each anneal to determine the effect on the resistivity. Results from the three additional anneals of the

Ti-SiC system, together with the I-V curves from the as-deposited and the 1,120° C initial annealing step, are given in the plots of Figure 6.

5. Ta-SiC I-V Results

Similar high-temperature annealing experiments were conducted with Ta metalization layers on equivalent SiC substrates used as Ti-SiC experiments. The resulting I-V curves are given in Figures 7–9. An outstanding feature of the Ta metalization on SiC was revealed by the I-V curve for the as-deposited sample as shown in Figure 7. It is noted that the as-deposited Ta layer produces a rectifying (Schottky barrier) contact as opposed to the ohmic contact of Ti-SiC. The rectifying behavior is indicated by the exponential relationship observed in the I-V measurement of the Ta-SiC sample. However, an ohmic contact was achieved in the Ta-SiC system after an anneal cycle of 1,120° C for 3 min as indicated by the I-V curve of Figure 8.

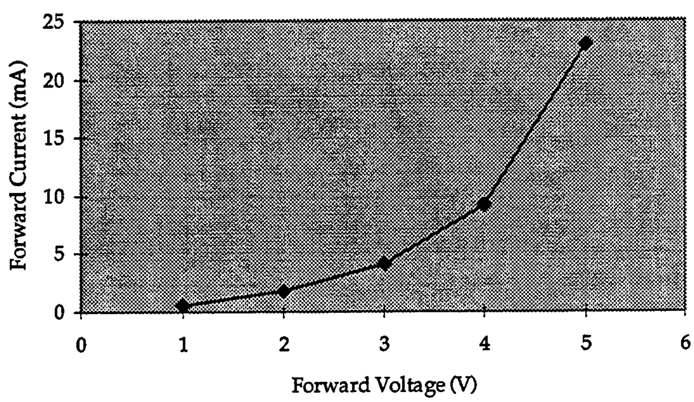

Figure 7. Current-Voltage Characteristic for Ta-SiC As-Deposited Sample.

Additional testing was performed with the Ta-SiC prototype sample at elevated temperatures of 600 and 1,000° C for varying burst lengths. The I-V results of these experiments are given in Figure 9, which indicate a stable I-V and, therefore, stable ohmic contact structure under all temperature conditions investigated.

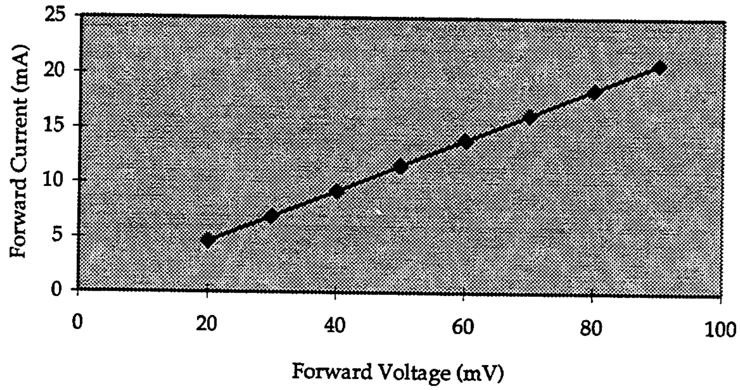

Figure 8. Current-Voltage Characteristic for Ta-SiC Sample Annealed at 1,120° C for 3 min.

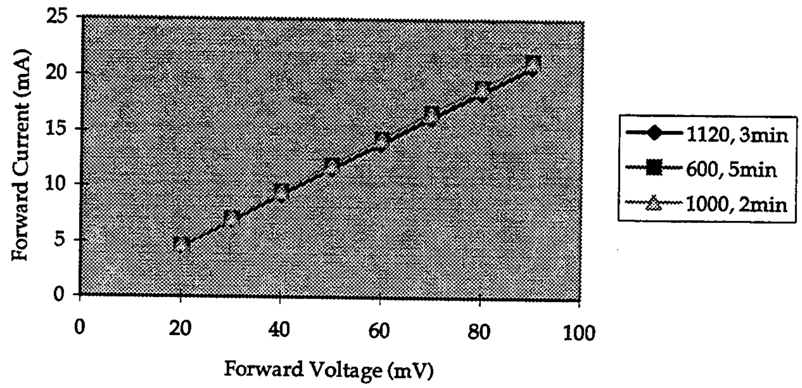

Figure 9. Current-Voltage Characteristic for Ta-SiC Sample Annealed at 600, 1,000, and 1,120° C.

6. Conclusions

Based upon the results from the I-V measurements obtained for the Ti and Ta metalization layers on the n-type SiC substrate employed in the experiments, it has been determined that both metals offer a reliable and stable electrical contact to n-type 4H SiC for elevated temperature operation. The temperature ranges considered for the Ti and Ta systems were 300–1,120° C and 600–1,120° C, respectively, and the temperature burst duration ranged from 2 to 5 min. The standard deviation calculated from the I-V measurements taken on the Ti-SiC system at the high-temperature bursts gives a value of a 0.167 ohms for an average sample resistivity of

4.45 ohms. This value of standard deviation represents approximately 3.8% of the average value of sample resistivity. The Ta-SiC system investigated through I-V measurements produced an even smaller standard deviation of only 0.05 ohms for a sample having an average resistivity of 4.25 ohms, which represents approximately 1.2% of the average sample resistivity. The results from the Ti and Ta on n-type SiC experiments are considered relevant to high-temperature electric weapons operating in the range of 300–1,120° C. Based upon the experiments and calculations performed, it is estimated that a mass reduction of between 45 and 60% of solid-state electronic material could be realized using SiC compared to Si for the electric gun applications considered here and operating at elevated temperatures for short periods of time. In order to completely assess the feasibility of high-temperature electronic materials for optimization of pulsed-power electric gun systems, however, it will be necessary to further characterize the fundamental long-term behavior of candidate material systems in anticipated environments. This will include continued long-term effects of high temperatures, large-amplitude current densities, and high electric fields upon the specific physical (electrical and mechanical) properties of candidate materials of interest.

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